Hard X-ray Emission from Cassiopeia A SNR

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Abstract. We report the results of extracting the hard X-ray continuum spectrum of Cas A SNR from RXTE/PCA Target of Opportunity observations (TOO) and CGRO/OSSE observations. The data can rule out the single thermal bremsstrahlung model for Cas A continuum between 2 and 150 keV. The single power law model gives a mediocre fit ($\sim$5%) to the data with a power-law index, Γ = 2.94$\pm$0.02. A model with two component (bremsstrahlung + bremsstrahlung or bremsstrahlung + power law) gives a good fit. The power law index is quite constrained suggesting that this continuum might not be the X-ray thermal bremmstrahlung from accelerated MeV electrons at shock fronts [1] which would have $\Gamma \simeq$2.26. With several SNRs detected by ASCA showing a hard power-law nonthermal X-ray continuum, we expect a similar situation for Cas A SNR which has Γ=2.98$\pm$0.09. We discuss the implication of the hardest nonthermal X-rays detected from Cas A to the synchrotron radiation model.

INTRODUCTION

X-ray observations of supernova remnants have been stimulated by recent reports of nonthermal power-law X-ray detections suggesting supernovae as sites of charged particle accelerations and sources of cosmic rays. The first strong evidence for charged particle acceleration near supernova shock fronts in the X-ray energy band is demonstrated by the morphological and spectral correlation between X-ray and radio emission from the bright NE and SW rims of SN 1006 [2]. The brightest radio emission regions show almost featureless power law X-ray spectra when compared with SN 1006 central region which is dominated by emission lines of highly ionized elements in a non-equilibrium ionization thermal plasma. The nonthermal X-ray component has been modeled as a synchrotron emission from electrons ac-

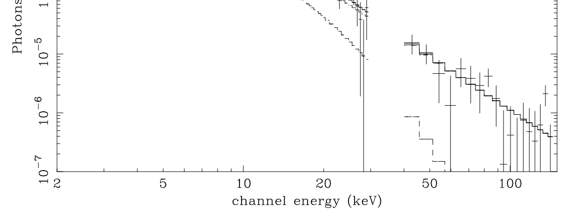

FIGURE 1. The thermal bremsstrahlung (kT=7.93 keV; dashed line) + power-law (Γ=2.98; dashed-dotted line) + 6 K X-ray line model produces a good fit (solid line) to the PCA & OSSE data (crosses) with a χ^2/dof=1.077, dof=62.

celerated to $\sim$100 TeV within shock fronts [3–5]. In this model, the radio spectrum is produced by synchrotron radiation of electrons accelerated to $\sim$GeV energies with the radio power-law index being less steep than the X-ray power-law index. Several similar evidences also have been demonstrated by ASCA measurement of RX J1713.7-3946 [6] and IC 443 [7], and RXTE and OSSE measurements of Cas A [8–10].

OSSE with a total accumulation time of 15×10^5 detector-seconds, detected a hard continuum between 40-150 keV from Cas A SNR at a 4σ confidence with a flux of $\sim9\times10^{-7}$ γ cm^{-2} s^{-1} keV^{-1} at 100 keV [10]. The detection is the hardest X-ray detection from a SNR without plerionic source. However, the shape of the continuum has not been strongly constrained. The continuum can either be a bremsstrahlung with kT$\simeq$35 keV or a power law with $\Gamma \simeq$3.06. In this paper, we use the 2-30 keV RXTE/PCA TOO and the 40-150 keV CGRO/OSSE Cas A data to better determine the shape of Cas A hard X-ray continuum.

RESULTS

The RXTE/PCA data used in this analysis is the TOO by RXTE on Aug. 2, 1996 with a total observing time of $\sim$4000 sec. We fit the 2-30 keV PCA data simultaneously with the 40-150 keV OSSE data. The results of fitting several models with one or two continuum plus about six emission lines from Si, S, Ar, Ca, and Fe are shown in Table 1. The line widths are fixed to 100 eV and the hydrogen column density toward Cas A is fixed at 1×10^{22} H cm^{-2} [11,12]. We find that a single thermal bremsstrahlung model for the data can be ruled out. Nevertheless, a single power law model gives a mediocre fit. We also find the two models that best fit the EXOSAT [12] and *Tenma* [11] data cannot give acceptable fits to the PCA and OSSE data. A two component model, either the bremsstrahlung + bremsstrahlung or the bremsstrahlung + power law, each gives an equally good fit. In Figure 1 for the current interest in a nonthermal power law model, we show the result of the thermal bremsstrahlung + power-law model fit to the data. The power law continuum is detected with a higher confidence level and the power-law index is more tightly constrained than using the OSSE data alone [10]. The PCA and OSSE data is consistent only at a 3.8% level with the X-ray bremsstrahlung from accelerated MeV electrons at shock fronts as suggested by Asvarov et al. [1] which would have $\Gamma = \alpha$+1.5=2.26 where α is the radio spectral index.

	χ^2/dof	dof	Prob.[b]
keV			
	1.934	64	1×10^{-5}
	1.313	64	0.047
1)$\times10^{-2}$	1.037	62	0.40
1)$\times10^{-1}$	1.078	62	0.31
	46.20	74	0
	82.88	74	0

ma data.
SAT data.

DISCUSSIONS

RXTE PCA + HEXTE in its AO-1 observing period detected a continuum between 10 and 60 keV [8,9]. The continuum is fitted well with a model of two Raymond-Smith thermal bremsstrahlung of kT = 0.7 keV and kT = 2.8 keV and a power law with Γ ~2.4 which exponentially steepens at e-fold 50 keV. The shape of the model is in good agreement with the result we find here.

The bremsstrahlung + bremsstrahlung model is expected in the reverse shock model. In this model, the hot temperature (T~23 keV) of the shocked circumstellar gas behind the blast-wave is consistent with the assumption that the blast-wave velocity is slightly larger than the observed median-filament velocity of 5500 km/s [13,14] and the circumstellar density n_H <1.5 cm^{-3}. The shocked gas temperature behind the reverse shock of T~4 keV suggests the swept up mass is ~6 $M_\odot$ and $n_H \simeq$1.4 cm^{-3} [14,15].

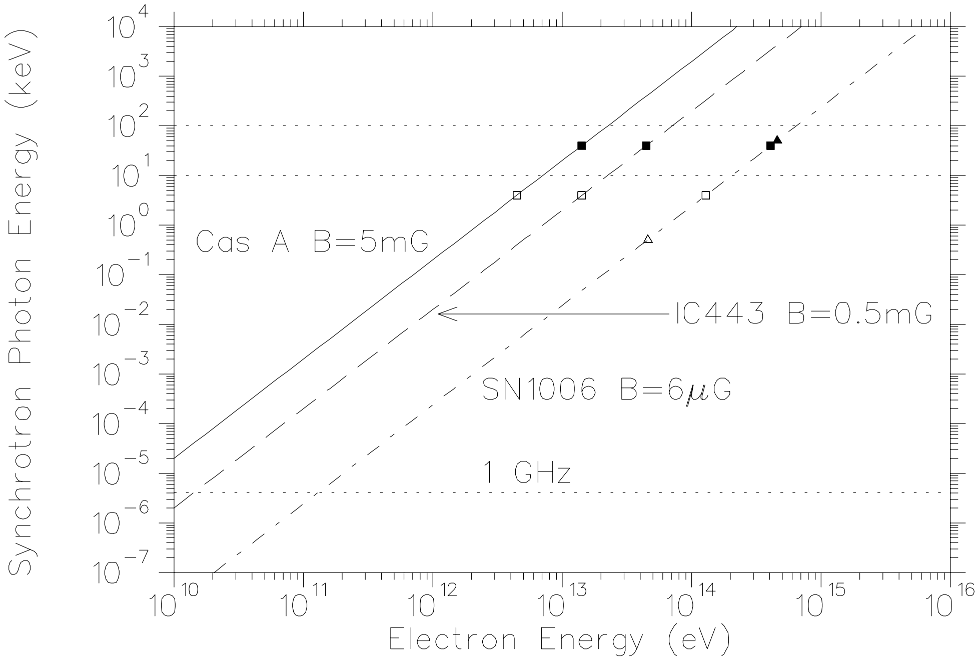

FIGURE 2. The synchrotron photon energy relation with the electron energy [2] for Cas A (solid line), IC 443 (dashed line), and SN 1006 (dashed-dotted line). The solid squares and the open squares mark the maximum electron energy constrained by the synchrotron energy loss (Eq.(1) of [4]) for f*R_J=1 and f*R_J=10, respectively. The solid triangles and the open triangles mark the maximum electron energy bounded by the age of the SNRs (Eq.(2) of [4]) for f*R_J=1 and f*R_J=10, respectively. This maximum energy is shown only for SN 1006 due to its low magnetic field. Synchrotron energy loss sets the maximum electron energy in Cas A and IC 443. The shock speed is assumed to be 5000 km/s in each case. f is the ratio of the electron mean free path to the electron gyroradius. R_J is the factor that contains the orientation of the shock relative to the magnetic field. The dotted lines shows some interesting synchrotron photon energies at 1 GHz, 10 keV, and 100 keV.

A summary of the detected nonthermal continuum from four SNRs is shown in Table 2. Cas A is of interest because from the 4 SNRs with measured nonthermal power-laws, it is the youngest, has the strongest magnetic field, its detected nonthermal energy is the highest, and it has the steepest X-ray and radio power-law indexes, of four SNRs with measured nonthermal power law. In Figure 2, we show for Cas A, IC 443, and SN 1006 how close their detected hard X-ray energies to the maximum synchrotron energies. The synchrotron energy is related to the maximum electron energy which is limited by the synchrotron energy loss and the SNR's age. Cas A, as the brightest radio SNR source, has the most intense magnetic field and therefore it causes the large synchrotron energy loss which limits Cas A's maximum electron energy. Figure 2 shows that the hard X-ray emission detected from Cas A by OSSE is near the cutoff synchrotron energy or indirectly to the maximum electron energy. Further Cas A measurements by OSSE may detect

TABLE 2. Comparison of the measured nonthermal continuum

SNR	Age (yrs)	Best Estimate of B	α	Measured Power Law Energy (keV)	Γ
SN1006	971	3-10 μG	0.56	0.5 - 20	2.95
RX J1713.7-3946	$\geq$1000	?	?	0.5 - 10	2.45
IC 443	1000	500 μG	$<$0.24	0.5 - 12	2.35
Cas A	317	1-5 mG	0.76	15-150	2.98

the cutoff energy and hence would provide the evidence that the nonthermal power law emission is the synchrotron radiation from accelerated electrons at the shock fronts near the maximum energy. Another evidence of the synchrotron radiation being the process for the nonthermal emission is the steepening of spectral index from radio to X-ray energy. It has been suggested that the turnover or break $\sim$0.25 keV is observed in SN 1006 spectra [5]. We expect the turnover in Cas A spectra is $\sim$1-10 keV due to Cas A's strong magnetic field. However, in order to observe this turnover in Cas A spectra, an X-ray imaging detector is needed because Cas A's thermal bremsstrahlung contributes substantially near this energy.

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